Dissertation Summary

On the Formation and Evolution of Stellar Bars in Galaxies[1]

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We have done a detailed study on the structural and kinematical properties of lenticular and early- and late-type spiral galaxies with bars, aiming to explore the formation and evolution processes of stellar bars in galaxies, and their implications on the global formation and evolution of galaxies.

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[1]See http://www.astro.iag.usp.br/∼dimitri/phdthesis/phdthesis.html where this work, originally written in Portuguese, is available.

Firstly, using high signal-to-noise spectra obtained along the major and minor axes of the bars in a sample of 14 face-on galaxies, we have determined the line of sight stellar velocity distribution in the bars' vertical axis, in several points, reaching 20" from the center. This was done with an algorithm properly developed for this task, which parameterizes the velocity distribution using Gauss-Hermite series (see, e.g., R. P. van der Marel & M. Franx 1993, ApJ, 407, 525), allowing for an accurate determination of the kinematical parameters. These spectra were observed with the 1.5 m ESO telescope at La Silla, Chile, and with the 2.3 m Steward Observatory telescope on Kitt Peak, Arizona. With these data, it was possible to develop a diagnostic tool that allows one to estimate the ages of bars, and distinguish between recently formed bars and evolved bars. Furthermore, we could evaluate the vertical structure of disks and bars in galaxies. We were able to separate evolved bars from recently formed ones based on the assumption that bars form within disks, thus having initially a thin vertical structure, which can be recognized by low values for the vertical stellar velocity dispersion, σ_z. As bars age, processes like vertical resonances (e.g., F. Combes & R. H. Sanders 1981, A&A, 96, 164) and the hose instability (e.g., D. Merritt & J. A. Sellwood 1994, ApJ, 425, 551) contribute to make σ_z higher, i.e., turning them vertically thick and possibly originating the characteristic boxy/peanut morphology (see Figure 1).

Secondly, through realistic N-body simulations with NEMO (P. J. Teuben 1995, ASP Conf. Ser., 77, 398), which represent a $2-3$ Gyr evolution of isolated galaxies with bulge, disk and a rigid dark matter halo, we have studied the necessary conditions to the formation of bars in galaxies with different morphological types (i.e., different bulge/disk ratios). In this way, we could also check the time scales involved in the processes which give bars an important vertical structure. These simulations show that the current scenario for bar formation (i.e., via the dynamical bar mode instability that originates globally in kinematically cold disks) is not able to explain naturally the existence of bars in

lenticular galaxies, which are kinematically hot stellar systems and have prominent bulges. While bars develop conspicuously in our N-body realizations of late-type spirals, the bar mode instability is suppressed in the realizations of galaxies with important bulges and kinematically hot disks. We thus suggest a new mechanism for bar formation in galaxies, which is based on the accommodation of the stellar orbits within a triaxial, or prolate, dark matter halo, which is sufficiently eccentric (D. A. Gadotti & R. E. de Souza 2003, ApJL, 583, 75). As we showed with N-body simulations which consist of only a spheroidal within such a halo, this mechanism rapidly produces perennial bars in hot stellar systems, and may be an explanation for the existence of barred galaxies in which the disk component is almost absent, a discovery which is also a product of this work (see below). Furthermore, this mechanism may account for the serious drawbacks confronted in the current scenario when applied to barred early-type spirals and lenticulars, as the triaxial halo may help in the onset of the bar mode instability in otherwise stable disks. We have also verified that a typical timescale for the thickening of bars, which cause the boxy/peanut morphology, is of the order of 1 Gyr. However, the values for the bar σ_z in our simulations after 1 Gyr are too low (< 50 Km/s) when compared to the ones we observed in evolved bars (~ 100 Km/s). Thus, we suggest that another process may be playing a relevant role after the vertical resonances and/or the hose instability to make σ_z as high as we observe in evolved bars. We have theoretically verified that the Spitzer-Schwarzschild mechanism, originally proposed for the Galaxy (see L. Spitzer & M. Schwarzschild 1951, ApJ, 114, 385), is quantitatively able to explain these observations if we assume that giant molecular clouds are twice as much concentrated along the bar as in the remaining of the disk. The timescales involved in this process should be $\sim 5 - 10$ Gyr, which is in agreement with the age differences between young and evolved bars we have estimated with optical colors (see below).

Thirdly, using images obtained in B, V, R, I and Ks for a sample of 19 galaxies, and images obtained in R for a sample of 51 galaxies, including elliptical galaxies, we have

performed a detailed structural analysis in galaxies covering the whole Hubble morphological sequence. The optical imaging was done with the 0.6 m telescope at the Pico dos Dias Observatory, Brazil, and with the 1.5 m Steward Observatory telescope on Mount Bigelow, Arizona. The infrared imaging was done with the 2.3 m Steward Observatory telescope on Kitt Peak, Arizona. We were then able to determine the structural parameters which better describe the bulge and the disk in these galaxies, as well as obtaining residual images which reveal important sub-structures. In order to perform this analysis we have developed a specific algorithm, and built an atlas of structural analysis in galaxies. This algorithm, named BUDDA (which stands for BUlge/Disk Decomposition Analysis[2]) performs a 2D bulge/disk decomposition on galaxy images, assuming a Sérsic bulge and an exponential disk. This part of the work revealed the existence of barred lenticular galaxies whose disk component is negligible (NGC 4608, NGC 5701 and possibly NGC 2217), as well as a difference in the optical colors of young and evolved bars which amounts to $B - V = 0.4$ mag. According to our knowledge on the evolution of stellar populations, this difference may be translated to a difference in age of the order of 10 Gyr. This result mean that bars may be, at least in some cases, a long standing structure. We have also found a correlation between the bulge Sérsic index n and the galaxy $B - I$ color gradient, in the sense that bulges with a more concentrated distribution of mass (i.e., with higher values for n) have flatter color gradients. As shown by D. A. Gadotti & S. dos Anjos (2001, AJ, 122, 1298), galaxies with flat color gradients are likely to be the ones in which the bar secular evolution processes related to bulge building are relevant. Thus, the correlation found corroborates the scenario in which bulges in lenticular and in spiral galaxies are, at least partially, formed through the secular evolutionary processes in bars. Moreover, our results showed that longer bars appear exclusively in galaxies with faint disks, that there is a correlation

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[2]See http://www.astro.iag.usp.br/∼dimitri/budda.html for the code's internet site.

between the color of the bar and the central disk intensity (in the sense that redder bars are in galaxies with fainter disks), and that evolved bars are longer than young bars, in average. Altogether, these results seem to indicate that, during its evolution, a bar grows stronger by capturing stars from the disk, which becomes fainter, in agreement with recent numerical and analytical results (E. Athanassoula 2003, MNRAS, 341, 1179). Thus, another possibility to explain the existence of barred galaxies with almost no disk is that their bars may have evolved so strongly by consuming their disks that there is almost no disk left.

Finally, our structural analysis also showed that around 1/3 of the elliptical galaxies harbor inner disks, which may be the result of recent mergers, and that visual morphological classification of galaxies is wrong in nearly 1/3 of the elliptical and lenticular galaxies, being equally easy to misclassify an elliptical as a lenticular and the other way around.

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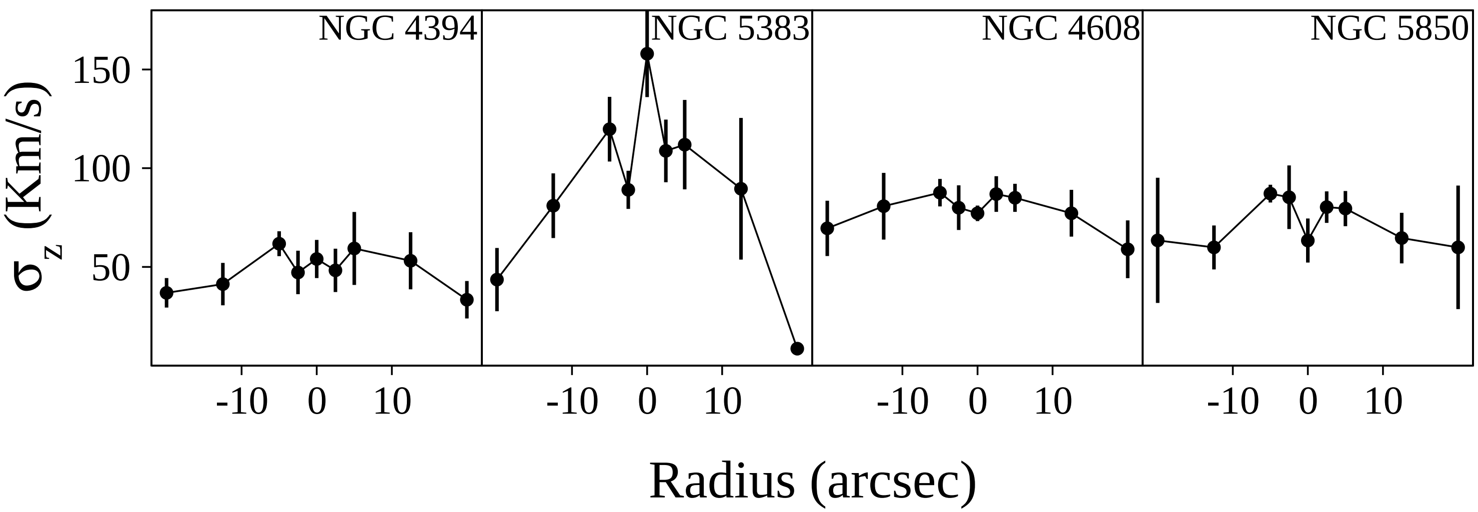
Fig. 1.— Measured values for σ_z along the bar major axis of 4 galaxies in our sample. The two panels at left are examples of recently formed bars while the ones at right are examples of evolved bars. In NGC 5383, the high values of σ_z in the inner region correspond to its bulge, while the drops at each side of the center are caused by its inner spiral arms. In NGC 5850, an inner bar identified in the BUDDA residual images is the likely reason for the noticeable drop in the center.



NGC 4394
NGC 5383
NGC 4608
NGC 5850
150
100
50
σz (Km/s)
-10
0
10
Radius (arcsec)